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ϵ_b Constraints on the Minimal $SU(5)$ and $SU(5)\times U(1)$ Supergravity Models

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Abstract

We have performed a systematic analysis to compute the one-loop electroweak corrections to the $Z\to b\bar{b}$ vertex in terms of ϵ_b and R_b in the context of the minimal $SU(5)$ and no-scale $SU(5)\times U(1)$ supergravity models. With the measured top mass, $m_t = 174\pm 10^{+13}_{-12}$ GeV , recently announced by CDF, we use the latest LEP data on ϵ_b and R_b ($\equiv \frac{\Gamma(Z\to b\bar{b})}{\Gamma(Z\to hadrons)}$) in order to constrain further the two models. We find that the present LEP data on ϵ_b and R_b constrain the two models rather severely. Especially, the low-$\tan\beta$ region is constrained more severely. $\tan\beta\lesssim 2.5$ (4.0) is excluded by ϵ_b at 90% C. L. for $m_t\gtrsim 170$ (180) GeV in the minimal $SU(5)$ (no-scale $SU(5)\times U(1)$) supergravity. Even more stringent constraint comes from R_b. It excludes $\tan\beta\lesssim 4.0$ at 90% C. L. for $m_t\gtrsim 160$ (170) GeV in the minimal $SU(5)$ (no-scale $SU(5)\times U(1)$) supergravity. We also find that the sign on μ in the

two models can be determined from ϵ_b and R_b at 90% C. L.

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I. INTRODUCTION

With the increasing accuracy of the LEP measurements, it has become more important than ever performing the precision test of the standard model (SM) and its extensions. A standard model fit to the latest LEP data yields the top mass, $m_t = 178 \pm 11^{+18}_{-19}$ GeV [1]. With this large top quark mass, the $Z \to b\bar{b}$ vertex contribution, which is proportional to m_t^2, becomes more significant, and can provide a powerful tool to constrain m_t experimetally. This is still very useful because the measured top mass from CDF [2], $m_t = 174 \pm 10^{+13}_{-12}$ GeV, has a large error bars and D0 gives just the lower bound on m_t, $m_t \gtrsim 131$ GeV [3]. With the improved measurement for the Z partial width to $b\bar{b}$, primarily due to the use of new life time-based techniques, one may be able to put more precise bound on m_t. The experimental value for $\Gamma(Z \to b\bar{b})$ has increased over the year, resulting in larger experimental value for R_b ($\equiv \frac{\Gamma(Z\to b\bar{b})}{\Gamma(Z\to hadrons)}$), and therefore rather small upper bound on m_t is favored in the SM [1]. One could certainly interpret this as a possible manifestation of new physics beyond the SM, where at one loop the negative standard top quark contributions are cancelled to a certain extent by the contributions from the new particles, thereby allowing considerably larger m_t than in the SM. In fact, the minimal supersymmetric standard model (MSSM) realizes this possibility.

Another very interesting observable which encodes the one loop corrections to the $Z \to b\bar{b}$ vertex is ϵ_b first introduced in Ref. [4]. In supergravity(SUGRA) models, radiative electroweak symmetry breaking mechanism [5] can be described by at most 5 parameters: the top-quark mass (m_t), the ratio of Higgs vacuum expectation values ($\tan\beta$), and three universal soft-supersymmetry-breaking parameters ($m_{1/2}, m_0, A$) [1].

In this work we explore the minimal $SU(5)$ SUGRA [7] and the no-scale $SU(5) \times U(1)$ SUGRA [8] in terms of ϵ_b parameter which encodes the one-loop corrections to the $Z \to b\bar{b}$ vertex. Moreover, we attempt to see how well these models can fit in rather uncomfortably

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[1]See, however, Ref. [6] for non-universal soft-supersymmetry breaking parameters

high 1993 LEP value for R_b ($\equiv \frac{\Gamma(Z\to b\bar{b})}{\Gamma(Z\to hadrons)}$).

II. THE MINIMAL $SU(5)$ AND $SU(5)\times U(1)$ SUGRA MODELS

The minimal $SU(5)$ and $SU(5)\times U(1)$ SUGRA models both contain, at low energy, the SM gauge symmetry and the particle content of the MSSM. A few crucial differences between the two models are:

(i) The unification groups are different, $SU(5)$ versus $SU(5)\times U(1)$.

(ii) The gauge coupling unification occurs at $\sim 10^{16}$ GeV in the minimal $SU(5)$ model whereas in $SU(5)\times U(1)$ model it occurs at the string scale $\sim 10^{18}$ GeV [9]. In $SU(5)\times U(1)$ SUGRA, the gauge unification is delayed because of the effects of an additional pair of $\mathbf{10}$,$\overline{\mathbf{10}}$ vector-like representations with intermediate-scale masses. The different heavy field content at the unification scale leads to different constraints from proton decay.

(iii) In the minimal $SU(5)$ SUGRA, proton decay is highly constraining whereas it is not in $SU(5)\times U(1)$ SUGRA.

The procedure to restrict 5-dimensional parameter spaces is as follows [10]. First, upon sampling a specific choice of $(m_{1/2}, m_0, A)$ at the unification scale and $(m_t, \tan\beta)$ at the electroweak scale, the renormalization group equations (RGE) are run from the unification scale to the electroweak scale, where the radiative electroweak breaking condition is imposed by minimizing the effective 1-loop Higgs potential, which determines the Higgs mixing term μ up to its sign. We also impose consistency constraints such as perturbative unification and the naturalness bound of $m_{\tilde{g}} \lesssim 1\,\text{TeV}$. Finally, all the known experimental bounds on the sparticle masses are imposed [2]. This prodedure yields the restricted parameter spaces for the two models.

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[2] We use the following experimental lower bounds on the sparticle masses in GeV in the order of gluino, squarks, lighter stop, sleptons, and lighter chargino: $m_{\tilde{g}} \gtrsim 150$, $m_{\tilde{q}} \gtrsim 100$, $m_{\tilde{t}_1} \gtrsim 45$, $m_{\tilde{l}} \gtrsim 43$, $m_{\chi_1^\pm} \gtrsim 45$.

Further reduction in the number of input parameters in $SU(5)\times U(1)$ SUGRA is made possible because in specific string-inpired scenarions for $(m_{1/2}, m_0, A)$ at the unification scale these three parameters are computed in terms of just one of them [11]. One obtains $m_0 = A = 0$ in the *no-scale* scenario and $m_0 = \frac{1}{\sqrt{3}} m_{1/2}$, $A = -m_{1/2}$ in the *dilaton* scenario [3].

The low energy predictions for the sparticle mass spectra are quite different in the two SUGRA models mainly due to the different pattern of supersymmetry radiative breaking. In the minimal $SU(5)$ SUGRA, all the squarks except the lighter stop and all the Higgs except the lighter neutral Higgs are quite heavy ($\gtrsim$ a few hundred GeV) whereas they can be quite light in the $SU(5)\times U(1)$ SUGRA. This difference leads to strikingly different phenomenology in the two models, for example in the flavor changing radiative decay $b\to s\gamma$ [13].

III. ONE-LOOP ELECTROWEAK RADIATIVE CORRECTIONS AND THE NEW ϵ PARAMETERS

There are several schemes to parametrize the electroweak vacuum polarization corrections [14–17]. It can be shown, by expanding the vacuum polarization tensors to order q^2, that one obtains three independent physical parameters. Alternatively, one can show that upon symmetry breaking three additional terms appear in the effective lagrangian [16]. In the (S,T,U) scheme [15], the deviations of the model predictions from the SM predictions (with fixed SM values for $m_t, m_{H_{SM}}$) are considered as the effects from "new physics". This scheme is only valid to the lowest order in q^2, and is therefore not applicable to a theory with light new particles comparable to M_Z. In the ϵ-scheme [4,18], on the other hand, the model predictions are absolute and also valid up to higher orders in q^2, and therefore this scheme is more applicable to the electroweak precision tests of the MSSM [19] and a class

[3]Note, however, that one loop correction changes this relation significantly [12].

of supergravity models [20].

There are two different ϵ-schemes. The original scheme [18] was considered in one of author's previous analyses [20,21], where $\epsilon_{1,2,3}$ are defined from a basic set of observables Γ_l, A^l_{FB} and M_W/M_Z. Due to the large m_t-dependent vertex corrections to Γ_b, the $\epsilon_{1,2,3}$ parameters and Γ_b can be correlated only for a fixed value of m_t. Therefore, Γ_{tot}, Γ_{hadron} and Γ_b were not included in Ref. [18]. However, in the new ϵ-scheme, introduced recently in Ref. [4], the above difficulties are overcome by introducing a new parameter ϵ_b to encode the $Z \to b\bar{b}$ vertex corrections. The four ϵ's are now defined from an enlarged set of Γ_l, Γ_b, A^l_{FB} and M_W/M_Z without even specifying m_t. This new scheme was adopted in a previous analysis by one of us (G.P.) in the context of the $SU(5) \times U(1)$ SUGRA models [22]. In this work we use this new ϵ-scheme. As is well known, the SM contribution to ϵ_1 depends quadratically on m_t but only logarithmically on the SM Higgs boson mass (m_H). Therefore upper bounds on m_t have a non-negligible m_H dependence: up to 20 GeV stronger when going from a heavy (≈ 1 TeV) to a light (≈ 100 GeV) Higgs boson. It is also known in the MSSM that the largest supersymmetric contributions to ϵ_1 are expected to arise from the $\tilde{t}$-$\tilde{b}$ sector, and in the limiting case of a very light stop, the contribution is comparable to that of the t-b sector. The remaining squark, slepton, chargino, neutralino, and Higgs sectors all typically contribute considerably less. For increasing sparticle masses, the heavy sector of the theory decouples, and only SM effects with a *light* Higgs boson survive. However, for a light chargino ($m_{\chi^\pm_1} \to \frac{1}{2}M_Z$), a Z-wavefunction renormalization threshold effect coming from Z-vacuum polarization diagram with the lighter chargino in the loop can introduce a substantial q^2-dependence in the calculation [19]. This results in a weaker upper bound on m_t than in the SM. The complete vacuum polarization contributions from the Higgs sector, the supersymmetric chargino-neutralino and sfermion sectors, and also the corresponding contributions in the SM have been included in our calculations [20]. However, the supersymmetric contributions to the non-oblique corrections except in ϵ_b have been neglected.

Following Ref. [4], ϵ_b is defined from Γ_b, the inclusive partial width for $Z \to b\bar{b}$, as

$$\epsilon_b = \frac{g_A^b}{g_A^l} - 1 \tag{1}$$

where g_A^b (g_A^l) is the axial-vector coupling of Z to b (l). In the SM, the diagrams for ϵ_b involve top quarks and $W^\pm$ bosons [23], and the contribution to ϵ_b depends quadratically on m_t ($\epsilon_b = -G_F m_t^2/4\sqrt{2}\pi^2 + \cdots$). In supersymmetric models there are additional diagrams involving Higgs bosons and supersymmetric particles. The charged Higgs contributions have been calculated in Refs. [24,25] in the context of a non-supersymmetric two Higgs doublet model, and the contributions involving supersymmetric particles in Refs. [26,27]. The main features of the additional supersymmetric contributions are: (i) a negative contribution from charged Higgs–top exchange which grows as $m_t^2/\tan^2\beta$ for $\tan\beta \ll \frac{m_t}{m_b}$; (ii) a positive contribution from chargino-stop exchange which in this case grows as $m_t^2/\sin^2\beta$; and (iii) a contribution from neutralino(neutral Higgs)–bottom exchange which grows as $m_b^2\tan^2\beta$ and is negligible except for large values of $\tan\beta$ (*i.e.*, $\tan\beta \gtrsim \frac{m_t}{m_b}$) (the contribution (iii) has been neglected in our analysis).

IV. RESULTS AND DISCUSSION

In Figure 1 we present our numerical results for ϵ_b in the two SUGRA models. $\alpha_S(M_Z) = 0.118$ and $m_b = 4.8$ GeV are used throughout the numerical calculations. We use the experimental value for ϵ_b, $\epsilon_b^{exp} = (0.9 \pm 4.2) \times 10^{-3}$, determined from the latest ϵ- analysis using the LEP and SLC data in Ref. [28]. The discontinuity in the chargino mass in the minimal model in the figure is simply due to the use of large steps in sampling the value of $m_{1/2}$. The values of m_t are chosen in such a way that the approximate ϵ_b-deduced m_t bounds are readily obtained from the figure. Only one value of m_t is displayed in the $SU(5)\times U(1)$ SUGRA because considerable portion of the model predictions are overlapped for two different values of m_t due to the steep rise in ϵ_b for a light chargino. The reason why the rise in ϵ_b in the $SU(5)\times U(1)$ SUGRA is much steeper than in the minimal $SU(5)$ SUGRA is that the stop mass scales with the chargino mass in the no-scale model whereas

it does not in the minimal model. Therefore, the light chargino effect in ϵ_b is optimized better in the no-scale $SU(5) \times U(1)$ SUGRA. This difference leads to different ϵ_b-deduced m_t bounds in the two models. The approximate bounds at 90% C. L. are $m_t \lesssim 175$ (185) GeV for the minimal $SU(5)$ (no-scale $SU(5) \times U(1)$) SUGRA. In the no-scale model, one can also determine the sign on μ to be positive for $m_t \gtrsim 180$ GeV. The lowest value of ϵ_b for a fixed m_t represents the lowest $\tan\beta$ for not too large $\tan\beta$ [4]. It is $\tan\beta = 1.5$ (4.0) for the minimal $SU(5)$ (no-scale $SU(5) \times U(1)$) SUGRA in Figure 1. From this, we obtain low $\tan\beta - m_t$ correlated bounds at 90% C. L., which are for $\tan\beta \lesssim 2.5$ (4.0), $m_t \lesssim 170(180)$ GeV in the minimal $SU(5)$ (no-scale $SU(5) \times U(1)$) SUGRA. Although the m_t values from CDF have rather large error bars at present, one can imagine an interesting situation in the near future where the m_t values from CDF turns out to fall between the above ϵ_b-deduced m_t bounds, disfavoring only one model.

The experimental value for $R_b (\equiv \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to hadrons)})$ from the 1993 LEP data are reported very recently to be rather high, 0.2192 ± 0.0018, in comparison with the SM predictions [1]. In an attempt to see how much the situation can improve in SUGRA models, we now calculate R_b in the two SUGRA models [5]. In Figure 2 we show the model predictions for R_b in the two models. As seen in the figure, the R_b constraint is much stronger than the ϵ_b constraint. The R_b-deduced m_t bounds at 90% C. L. are $m_t \lesssim 165$ (175) GeV for the minimal $SU(5)$ (no-scale $SU(5) \times U(1)$) SUGRA. From the figure, one can also put bounds on the chargino mass, which are $m_{\chi_1^\pm} \lesssim 85$ (70) GeV for $m_t \gtrsim 160$ (170) GeV for the minimal $SU(5)$ (no-scale $SU(5) \times U(1)$) SUGRA. Similarly, one can also obtain bounds on the lighter stop mass given by $m_{\tilde{t}_1} \lesssim 500$ (190) GeV for $m_t \gtrsim 160$ (170) GeV for the minimal $SU(5)$ (no-scale

[4]For large $\tan\beta (\gtrsim \frac{m_t}{m_b})$, the charged Higgs diagram gets a significant contribution proportional to $-m_b^2 \tan^2\beta$ coming from the charged Higgs coupling to b_R, thereby driving ϵ_b even below the value corresponding to the lowest $\tan\beta$.

[5]We use the expression for R_b in terms of ϵ's given in Ref. [4]

$SU(5)\times U(1)$) SUGRA. Therefore, in the minimal $SU(5)$ (no-scale $SU(5)\times U(1)$) SUGRA, if the top turns out to be heavier than 160 (170) GeV, then only the lighter chargino may be detected at LEPII. The $\tan\beta$-dependence is very pronounced in the no-scale model for $\mu > 0$. The low values of $\tan\beta$ are as indicated in the figure. For $\tan\beta = 2$, the dotted curve becomes nearly flat as the chargino mass becomes large. This is because the charged Higgs contribution nearly cancels the chargino contribution [26], making R_b get saturated much faster to the SM value. As in the ϵ_b constraint above, the low $\tan\beta - m_t$ correlated bounds at 90% C. L. are obtained as follows: for $\tan\beta \lesssim 4.0$, $m_t \lesssim 160$ (170) GeV in the minimal $SU(5)$ (no-scale $SU(5)\times U(1)$) SUGRA. In the no-scale model, $\tan\beta \lesssim 2$ is excluded even at 95% C. L. for $m_t \gtrsim 170$ GeV. From R_b, one can also determine μ to be positive in both models. It is very interesting for one to see that the low-$\tan\beta$ region is severely constrained by both constraints above. We would like to stress here the fact that our calculations are fairly accurate in the low-$\tan\beta$ region because the diagrams neglected in the calculations can be safely neglected there. The major features of the constraints from ϵ_b and R_b for the two SUGRA models are summarized in the Table 1.

V. CONCLUSIONS

We have computed the one-loop electroweak corrections to the $Z \to b\bar{b}$ vertex in terms of ϵ_b and R_b in the context of the minimal $SU(5)$ and no-scale $SU(5)\times U(1)$ supergravity models. We use the latest LEP data on ϵ_b and R_b in order to constrain further the two models. We find that the present LEP data on ϵ_b and R_b constrain the two models rather severely. Especially, the low-$\tan\beta$ region is constrained more severely. $\tan\beta \lesssim 2.5$ (4.0) is excluded by ϵ_b at 90% C. L. for $m_t \gtrsim 170$ (180) GeV in the minimal $SU(5)$ (no-scale $SU(5)\times U(1)$) SUGRA. Even more stringent constraint comes from R_b. It excludes $\tan\beta \lesssim 4.0$ at 90% C. L. for $m_t \gtrsim 160$ (170) GeV in the minimal $SU(5)$ (no-scale $SU(5)\times U(1)$) SUGRA. We also find that the sign on μ in the two models can be determined from ϵ_b and R_b at 90% C. L. This can be of special interest in the minimal $SU(5)$ because the low-$\tan\beta$ region is

phenomenologically favored by the measured ratio m_b/m_τ. We also find that the sign on μ in the two models can be determined from ϵ_b and R_b at 90% C. L.

With improved measurement on the top mass by CDF in the near future, there may be an amusing possibility that one could favor one model over the other from the $Z \to b\bar{b}$ constraints. And also, in the no-scale $SU(5) \times U(1)$ SUGRA, if the top turns out to be heavier than 170 GeV, then only the lighter chargino lighter than 80 GeV may be detected at LEPII.

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FIGURES

FIG. 1. The predictions for ϵ_b versus the lighter chargino mass in the minimal $SU(5)$ SUGRA for $m_t = 160, 175$ GeV (top row) and in the no-scale $SU(5)\times U(1)$ SUGRA for $m_t = 180$ GeV (bottom row). The values of m_t are as indicated. The points above the horizontal solid line are allowed at 90% C.L.

FIG. 2. The predictions for R_b versus the lighter chargino mass in the minimal $SU(5)$ SUGRA for $m_t = 160$ GeV (top row) and in the no-scale $SU(5)\times U(1)$ SUGRA for $m_t = 170$ GeV (bottom row). The values of $\tan\beta$ are as indicated near the dotted curves (bottom row). The points above the horizontal solid lines are allowed at 90 or 95% C.L.

TABLES

TABLE I. The major features of the constraints from ϵ_b and R_b for the two SUGRA models considered.

	Minimal $SU(5)$	no-scale $SU(5)\times U(1)$
ϵ_b (90% C.L.)	$m_t \lesssim 175$ GeV for any $\tan\beta$	$m_t \lesssim 185$ GeV for any $\tan\beta$
	$m_t \lesssim 170$ GeV for $\tan\beta \lesssim 2.5$	$m_t \lesssim 180$ GeV for $\tan\beta \lesssim 4$
R_b (90% C.L.)	$m_t \lesssim 165$ GeV for any $\tan\beta$	$m_t \lesssim 175$ GeV for any $\tan\beta$
	$m_t \lesssim 160$ GeV for $\tan\beta \lesssim 4$	$m_t \lesssim 170$ GeV for $\tan\beta \lesssim 4$
	For $m_t \gtrsim 160$ GeV,	For $m_t \gtrsim 170$ GeV,
	$m_{\chi_1^\pm} \lesssim 85$ GeV and $m_{\tilde{t}_1} \lesssim 500$ GeV	$m_{\chi_1^\pm} \lesssim 70$ GeV and $m_{\tilde{t}_1} \lesssim 190$ GeV